ORIGINAL ARTICLE

Challenging anatomy, comparable outcomes: a multicenter propensity score-matched analysis of robotic hepatectomy in posterosuperior versus anterolateral segments

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Abstract

Introduction: Robotic liver resection has become increasingly adopted for minor hepatectomies, including lesions in the anatomically challenging posterosuperior (PS) segments. This study compares the perioperative and pathological outcomes of robotic minor resections in PS versus anterolateral (AL) segments across high-volume centers in Europe.

Materials and methods: A multicenter database of 730 robotic liver resections performed from 2011 to 2023 in nine European institutions was reviewed. After excluding major hepatectomies, patients were analyzed in three steps: overall cohort, comparison of PS vs AL resections, and two consecutive propensity score matches.

Results: PS resections consistently had longer operative times, increased blood loss, and increased frequency and duration of Pringle maneuver use in all analyses. Following propensity matching, post-operative outcome measures such as overall morbidity, major complications, readmission, mortality, length of stay, and R1 rates were similar for PS and AL resections.

Discussion: Despite greater intraoperative complexity, robotic surgery seems to offset the technical disadvantages of PS segments to obtain postoperative and pathological results comparable to AL resections.

Conclusion: Robotic minor liver resections in PS segments are safe and feasible when performed in experienced centers, supporting their broader adoption in advanced minimally invasive hepatobiliary surgery.

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Introduction

Over the last two decades, minimally invasive liver surgery (MILS) has progressively expanded, supported by technological advances and increasing surgical expertise. Both laparoscopic and robotic techniques have shown advantages over open surgery in terms of reduced postoperative pain, shorter hospital stays, lower blood loss, and quicker recovery, maintaining oncologic safety in appropriately selected patients.[1−3] The robotic platform has gained particular interest within MILS for complex liver resections due to its improved dexterity, filtration of physiological tremors, and stable three-dimensional vision, all of which can contribute to accurate parenchymal transection and dissection in deep or narrow anatomical spaces.[4−6]

Despite these developments, the resection of lesions located in the so-called posterosuperior (PS) liver segments, namely segments 1, 4a, 7, and 8, is still considered demanding due to the restricted working space beneath the diaphragm, difficult angulation of instruments, and challenging exposure. Therefore, these segments are "difficult-to-access" in conventional laparoscopy. On the other side, anterolateral (AL) segments (2, 3, 4b, 5, 6) are generally considered more suitable for minimally invasive approaches because of their favorable anatomical position and easier mobilization. Historically, these anatomical constraints favored the use of open surgery for PS lesions or highly specialized laparoscopic expertise when dealing with such lesions.

Part of these limitations has been overcome by the introduction of robotic liver surgery. Many studies showed that Robotic Liver Resection (RLR) offers better ergonomics and precision, therefore facilitating resections in PS segments with acceptable safety profiles. Propensity-matched analyses showed that RLR in posterior or superior segments may reduce conversion rates and blood loss when compared with laparoscopic or even open surgery, while attaining comparable oncologic margins.[7−11] Recent multicenter series further confirmed the feasibility of robotic minor resections in challenging locations, emphasizing favorable short-term outcomes, especially in high-volume hepatobiliary units.[12−14] Notably, modern European groups significantly contributed to defining the role of robotics in complex hepatobiliary surgery, documenting expanding indications and refined technical strategies.[13−15]

However, despite the apparent advantages of robotic approaches in anatomically challenging resections, few studies have directly compared RLR for PS segments and for AL segments. It is currently unknown whether the anatomic complexity of PS segments translates into measurable differences in operative time, blood loss, conversion rates, postoperative morbidity, or length of stay using the robotic platform. Most prior reports group resections by their approach (robotic vs. laparoscopic) rather than segmental location, or are limited by small sample sizes or single-center design.

The current study, therefore, evaluates perioperative outcomes of RLR in PS vs. AL segments using a large European retrospective and multicentric database to provide a strong comparison of safety, feasibility, and short-term outcomes between these two anatomically distinct regions by incorporating two sequential propensity-score matching (PSM) analyses to mitigate baseline imbalances, including cirrhosis, lesion focality, anatomical resection, and sex. To the best of our knowledge, this represents one of the largest multicentre evaluations specifically comparing RLR of PS and AL liver segments.

Material and methods

This retrospective multicenter cohort study included patients who underwent RLR in nine high-volume European hepatobiliary centers between 2011 and 2023. All centers are recognized referral units for MILS and follow standardized perioperative protocols aligned with international recommendations on laparoscopic and robotic liver resections.[11,12]

The study was conducted in accordance with the ethical standards of the Declaration of Helsinki and was approved by all participating centers. Due to the retrospective design, informed consent was waived according to local regulations.

From an initial database of 730 consecutive robotic liver resections, we excluded the following.

- Major hepatectomies (resection of ≥3 Couinaud segments, following Brisbane 2000 terminology[16]);
- Two-stage hepatectomies;
- Combined thoracic or bowel procedures;
- Palliative debulking procedures;
- Incomplete intraoperative or postoperative data.

For the final study cohort, only minor RLR were included, defined as wedge resections, anatomical segmentectomies, or bisegmentectomies involving one or two contiguous segments.[16]

We stratified patients according to the anatomical location of the resected segment(s).

- PS group: Couinaud segments 1, 4a, 7, 8 are considered "difficult-to-access" in minimally invasive surgery because of limited exposure and restricted working space[1,13];
- AL group: segments 2, 3, 4b, 5, 6, considered more favorable for minimally invasive approaches.[13]

Resections that involved multiple segments were classified based on the most anatomically challenging segment.

All cases were discussed in multidisciplinary tumor boards.

Cirrhosis was defined histologically or by radiologic criteria associated with clinical features consistent with the EASL definition of chronic liver disease.[17]

All the procedures were performed by expert hepatobiliary surgeons with proven experience in both open and minimally invasive surgery using a four-arm robotic platform da Vinci Xi® or X®, Intuitive Surgical®, Sunnyvale, CA. At the beginning of the surgical procedure, an intraoperative ultrasound (IOUS) was systematically performed. The Pringle maneuver was prepared routinely at the beginning of the surgical procedure, too, but it was used according to each center's experience. However, in almost all cases, intermittent clamping was preferred. The parenchymal liver transection was performed with different techniques, energies, and devices depending on the surgeon's experience and habits.

Anatomical resections were defined in accordance with Couinaud's segmental anatomy and the Brisbane guidelines.[16] Postoperative complications within 90 days were classified using the Clavien—Dindo classification.[18] Major complications were defined as grade ≥ III. Pathologic examination evaluated margin width, and the R1 parenchymal margin was defined as <1 mm, according to contemporary oncologic standards for liver resection.[19]

Continuous variables were presented as means and categorical variables as counts and percentages. Normality was assessed by the Shapiro—Wilk test.

Three levels of comparison were carried out.

1. Unmatched analysis comparing PS and AL groups;
2. First PSM was based on preoperative and surgical factors, which were significantly imbalanced at baseline;
3. Second PSM incorporating variables that remained imbalanced after the first matching.

The propensity score was calculated using a logistic regression model, and subjects were matched using nearest neighbor 1:1 matching with a caliper of 0.2 of the standard deviation of the logit of the propensity score. The balance across matched groups was tested using standardized mean differences (SMD <0.1 considered acceptable).

Comparisons between groups were performed by using Student's t-test or the Mann—Whitney U test for continuous variables and χ^2 or Fisher's exact test for categorical variables.

For purposes of testing, a two-sided p-value <0.05 was considered statistically significant.

All the statistical analyses were done by using SPSS v.29.0 (IBM Corp.).

Results

After exclusion of major hepatectomies, a total of 606 patients who underwent minor RLR were included in the analysis (Table 1).

The mean age was 63.8 years, 48.3 % were older than 65 years, and 39.3 % were female. Cirrhosis was present in 37.8 % of patients, and 49 % had a monofocal lesion. The mean tumor size was 33.1 mm, while anatomical resections accounted for 43 % of all procedures.

Table 1 Overall cohort

Variables	n = 606
Age (yr), mean	63,8
Age >65 years old, n (%)	48,3
Female, n (%)	39,3
BMI (kg/m2), mean	26,6
ASA score ≥ III, n (%)	42,7
Charlson comorbidity score, mean	6,1
Previous open abdominal surgery, n (%)	47,5
Previous laparoscopic abdominal surgery, n (%)	22,3
Cirrhosis, n (%)	37,8
Monofocal lesion, n (%)	49
Tumor: Size of the biggest lesion (mm), mean	33,1
TAMPA score, mean	12
Anatomical resection, n (%)	43
Conversion to open, n (%)	3,8
Conversion to laparoscopy, n (%)	0
Operative time (min), mean	239,1
Estimated blood loss (mL), mean	216,15
Blood transfusion, n (%)	4,4
Pedicule clamping, n (%)	39,8
Pedicule clamping duration (min), mean	40,5
Post-operative complication, n (%)	51,5
Biliary leakage, n (%)	2,1
Hemorrhage, n (%)	1,5
Prolonged pain, n (%)	5,9
Ascites, n (%)	4,1
Pulmonary infection, n (%)	5,3
Other infections, n (%)	3,5
Severe complication (Clavien-Dindo 3–4), n (%)	4
In-hospital mortality (Clavien-Dindo 5), n (%)	0,7
Re-intervention, n (%)	0,8
ICU stay (days), mean	0,7
Total hospital stay (days), mean	5,4
Surgical margins (mm), mean	11,4
R1 parenchymal, n (%)	4,1
Readmission at 90 days, n (%)	4,8

BMI, body mass index; ASA, American Society of Anesthesiologists; ICU, intensive care unit.

Intraoperatively, the mean operative time was 239.1 min, with a mean EBL of 216 mL. Conversion to open surgery occurred in 3.8 %, and the Pringle maneuver was applied in 39.8 % of cases, with a mean clamping time of 40.5 min.

Postoperative complications occurred in 51.5 %, with 4 % of major complications (Clavien-Dindo ≥ III); the in-hospital mortality rate was 0.7 %. The mean hospital stay was 5.4 days, and the mean surgical margin was 11.4 mm, with an R1 parenchymal margin in 4.1 %.

Among the 606 patients, 206 (34 %) underwent resections in posterosuperior segments and 400 (66 %) in anterolateral segments (Table 2).

The two groups were comparable with respect to age, sex, comorbidity burden, body mass index (BMI), and prior abdominal surgery.

However, there were three important differences.

- Cirrhosis was more frequent in AL resections (41.5 % vs 30.6 %; p = 0.011).
- Monofocal lesions were more common in AL (81.5 % vs 65 %; $p < 0.001$).
- Anatomical resections were done more frequently in AL (49.7 % vs 30.1 %; $p < 0.001$).

Table 2 Comparison of PS vs AL resection

Variables	Postero-Superior n = 206	Antero-Lateral n = 400	p-value
Age (yr), mean	63,6	64	0,721
Age >65 years old, n (%)	47,1	49	0,669
Female, n (%)	36	41	0,254
BMI (kg/m2), mean	26,5	26,6	0,985
ASA score ≥ III, n (%)	40,3	44	0,388
Charlson comorbidity score, mean	6,3	6	0,263
Previous open abdominal surgery, n (%)	50	46,2	0,392
Previous laparoscopic abdominal surgery, n (%)	23,8	21,5	0,537
Cirrhosis, n (%)	30,6	41,5	**0,011**
Monofocal lesion, n (%)	65	81,5	**< 0,001**
Tumor: Size of the biggest lesion (mm), mean	32,8	33,3	0,755
TAMPA score, mean - median	13,9	10,9	**< 0,001**
Anatomical resection, n (%)	30,1	49,7	**< 0,001**
Conversion to open, n (%)	6,8	2,2	**0,012**
Operative time (min), mean	263	226,7	**< 0,001**
Estimated blood loss (mL), mean	258	194,6	**0,003**
Blood transfusion, n (%)	4,4	4,5	1000
Pedicule clamping, n (%)	48,5	35,2	**0,002**
Pedicule clamping duration (min), mean	47,2	35,6	**< 0,001**
Post-operative complication, n (%)	47,6	53,5	0,171
Biliary leakage, n (%)	1,9	2,2	1000
Hemorrhage, n (%)	1,4	1,5	1000
Prolonged pain, n (%)	3,8	7	0,148
Ascites, n (%)	4,8	3,7	0,523
Pulmonary infection, n (%)	6,8	4,5	0,252
Other infections, n (%)	2,8	3,7	0,815
Severe complication (Clavien-Dindo 3–4), n (%)	4,4	3,7	0,826
In-hospital mortality (Clavien-Dindo 5), n (%)	1,5	0,2	0,116
Re-intervention, n (%)	0,2	0,01	0,666
ICU stay (days), mean	0,7	1	0,068
Total hospital stay (days), mean	5,6	5,4 -5	0,309
Surgical margins (mm), mean	10,6	11,8	0,077
R1 parenchymal, n (%)	4,8	3,7	0,523
Readmission at 90 days, n (%)	3,9	3,7	0,109

BMI, body mass index; ASA, American Society of Anesthesiologists; ICU, intensive care unit.

The TAMPA difficulty score was significantly higher in PS resections (mean 13.9 vs 10.9; $p < 0.001$), reflecting the greater technical complexity of these segments.

As expected, PS resections were associated with increased operative difficulty with longer operative time (263 min vs 226.7 min; $p < 0.001$), higher EBL (258 mL vs 194.6 mL; $p = 0.003$), more frequent (48.5 % vs 35.2 %; $p = 0.002$) and longer (47.2 vs 35.6 min; $p < 0.001$) use of Pringle maneuver and higher rates of conversion to open surgery (6.8 % vs 2.2 %; $p = 0.012$).

Despite greater operative complexity, postoperative outcomes did not differ significantly in terms of overall complications, major complications, mortality, length of stay, and rates of R1 margin. These findings suggest that although PS resections are more technically demanding, they do not result in inferior postoperative outcomes.

A PSM was therefore performed based on statistically significant preoperative data (cirrhosis, monofocal lesions, and anatomical resections) to standardize the two cohorts. This produced 179 PS and 179 AL matched patients (Table 3).

Among the baseline characteristics, groups were well balanced for all variables, except for sex, which remained significantly different (Female: 33.5 % PS vs 45.8 % AL, $p = 0.023$). Otherwise, after matching, results have not changed

Table 3 First PSM

Variables	Postero-Superior n = 179	Antero-Lateral n = 179	p-value
Age (yr), mean	64,3	63,9	0,803
Age >65 years old, n (%)	49,2	48,6	1000
Female, n (%)	33,5	45,8	**0,023**
BMI (kg/m2), mean	26,6	26,8	0,697
ASA score ≥ III, n (%)	41,3	47,5	0,266
Charlson comorbidity score, mean	6,4	6,2	0,373
Previous open abdominal surgery, n (%)	49,7	48	0,833
Previous laparoscopic abdominal surgery, n (%)	24	21,8	0,706
Tumor: Size of the biggest lesion (mm), mean	32,6	33,5	0,624
TAMPA score, mean	14,2	10,6	**< 0,001**
Conversion to open, n (%)	6,1	2,8	0,200
Operative time (min), mean	258,2	218,8	**< 0,001**
Estimated blood loss (mL), mean	247,5	185	**0,017**
Blood transfusion, n (%)	4,5	5,6	0,810
Pedicule clamping, n (%)	50,8	34,1	**0,002**
Pedicule clamping duration (min), mean	25,2	11,2	**< 0,001**
Post-operative complication, n (%)	45,8	55,3	0,091
Biliary leakage, n (%)	2,2	3,3	0,750
Hemorrhage, n (%)	1,1	2,2	0,685
Prolonged pain, n (%)	3,3	8,8	0,070
Ascites, n (%)	3,9	3,3	1000
Pulmonary infection, n (%)	6,6	3,9	0,346
Other infections, n (%)	3,3	3,9	0,599
Severe complication (Clavien-Dindo 3–4), n (%)	4,5	6,1	0,638
In-hospital mortality (Clavien-Dindo 5), n (%)	0,5	0,5	1000
Re-intervention, n (%)	0,5	1,7	0,623
ICU stay (days), mean	0,65	0,66	0,962
Total hospital stay (days), mean	5,5	5,4	0,807
Surgical margins (mm), mean	10,8	12,1	0,112
R1 parenchymal, n (%)	3,9	4,5	1000
Readmission at 90 days, n (%)	5,6	4,5	0,810

BMI, body mass index; ASA, American Society of Anesthesiologists; ICU, intensive care unit.

much, with operative time, EBL, frequency, and duration of Pringle maneuver still statistically relevant. At the same time, postoperative parameters did non differ significantly.

A second PSM including sex created 157 PS and 157 AL matched cases (Table 4).

Both groups were completely comparable for all baseline variables; however, in spite of robust matching, several markers of procedural complexity remained significantly different. Operative time was longer in the PS group: 258.7 min compared with the AL group at 220.3 min ($p < 0.001$). Similarly, estimated blood loss was higher in PS patients at 245.6 mL versus 189.8 mL ($p < 0.001$). Moreover, the Pringle maneuver was employed more frequently in the PS group: 51.6 % versus 35.7 % ($p = 0.006$), and clamping duration was strikingly longer: 26.1 min versus 11 min in the AL group ($p < 0.001$). Otherwise, there were no significant differences in postoperative outcomes between the PS and AL groups.

Discussion

This multicenter European study compared the perioperative outcomes of minor RLR performed in PS versus AL segments. In both unmatched and propensity-matched analyses, PS resections consistently demonstrated features of increased intraoperative complexity, as reflected by longer operative time, higher EBL, more frequent application of the Pringle maneuver, and longer clamping duration. Despite these technical challenges, postoperative outcomes, including overall and major

Table 4 Second PSM

Variables	Postero-Superior n = 157	Antero-Lateral n = 157	p-value
Age (yr), mean	64,4	64,3	1000
Age >65 years old, n (%)	49,7	49	1000
BMI (kg/m2), mean	26,7	27	0,509
ASA score ≥ III, n (%)	42,7	47,8	0,562
Charlson comorbidity score, mean	6,4	6,3	0,858
Previous open abdominal surgery, n (%)	48,4	47,8	1000
Previous laparoscopic abdominal surgery, n (%)	36,3	28,7	0,893
Tumor: Size of the biggest lesion (mm), mean	32,7	32,8	0,990
TAMPA score, mean	14,4	10,8	**< 0,001**
Conversion to open, n (%)	5,1	1,3	0,104
Operative time (min), mean	258,7	220,3	**< 0,001**
Estimated blood loss (mL), mean	245,6	189,8	**< 0,001**
Blood transfusion, n (%)	4,4	5,7	0,798
Pedicule clamping, n (%)	51,6	35,7	**0,006**
Pedicule clamping duration (min), mean	26,1	11	**< 0,001**
Post-operative complication, n (%)	44,6	56	0,055
Biliary leakage, n (%)	2,5	3,2	1000
Hemorrhage, n (%)	1,3	2,5	0,684
Prolonged pain, n (%)	3,8	8,3	0,154
Ascites, n (%)	3,2	3,8	1000
Pulmonary infection, n (%)	6,7	4,4	0,619
Other infections, n (%)	3,8	5,1	0,786
Severe complication (Clavien-Dindo 3–4), n (%)	4,4	6,7	0,619
In-hospital mortality (Clavien-Dindo 5), n (%)	0,6	0,6	1000
Re-intervention, n (%)	0,6	1,9	0,623
ICU stay (days), mean	0,65	0,7	0,804
Total hospital stay (days), mean	5,5	5,6	0,737
Surgical margins (mm), mean	10,9	21,2	0,114
R1 parenchymal, n (%)	4,4	4,4	1000
Readmission at 90 days, n (%)	10	4,4	0,619

BMI, body mass index; ASA, American Society of Anesthesiologists; ICU, intensive care unit.

complications, 90-day readmission, mortality, and R1 parenchymal margin rates, remained comparable between PS and AL resections following matching. These findings suggest that the robotic platform may mitigate the clinical impact of anatomical difficulty inherent to PS segments when procedures were performed in experienced centers.

Our findings reinforce and expand previous evidence regarding the feasibility and safety of RLR even in anatomically challenging segments. Montalti *et al*. recently published a propensity score–matched comparison demonstrating that in the PS segments, robotic resections were associated with longer operative times and longer inflow occlusion, with comparable blood loss, complications, and oncologic margins compared with laparoscopic resections, concluding that the robotic platform facilitated access to difficult locations without compromising safety.[1] Similar findings were described by Nota *et al*., whose early multicenter experience with robotic resections in segments 7 and 8 documented acceptable blood loss, low conversion rates, and favorable postoperative outcomes despite the technical demands of these segments.[3]

Larger, more recent comparative studies find robotic systems can help overcome limitations that were historically associated with MILS in PS segments. Nota *et al*. demonstrated that robotic minor resections in PS segments, compared with open surgery in a multinational propensity-matched study, resulted in significantly shorter hospital stays and comparable morbidity, suggesting perioperative advantages even when compared with conventional open approaches.[2] Since that time, meta-analyses have consolidated the evidence. Lai *et al*. showed that robotic surgery offers reduced conversion rates and equivalent morbidity compared with laparoscopic liver resection, with particular advantages in difficult locations.[4] Similarly, Hu *et al*. analyzed outcomes in HCC and found that RLR achieved equivalent oncologic outcomes to open or laparoscopic resections while reducing blood loss and length of stay.[5]

The most comprehensive recent contribution is the international propensity-matched study by Sijberden *et al*., which analyzed more than 10,000 resections and showed that RLR was associated with less blood loss, less transfusion, fewer conversions, and better "textbook outcomes" compared to laparoscopic approaches for a wide spectrum of resections.[6] Our findings continue this contemporary trend in that, although PS resections are more demanding, it would seem that the robotic approach neutralizes these challenges with respect to postoperative morbidity and oncologic adequacy.

In the context of European experience, our findings are in good agreement with those in other multicenter analyses on robotic liver surgery—particularly in HCC—demonstrated favorable morbidity profiles, low conversion rates, and solid oncologic outcomes, supporting an expanded role for robotic approaches in complex settings.[8–10] Very recently, we reported excellent perioperative and pathologic outcomes in robotic resections for HCC, emphasizing that RLR can be safely applied even in cirrhotic patients or in deep-located tumors when performed in high-volume centers.[9] These findings confirm the observations from our propensity-matched groups, in which cirrhosis did not adversely affect outcomes following PS RLR.

In addition to the increasing body of evidence supporting the use of RLR in PS segments, several recent meta-analyses provide important context for the interpretation of our findings. A 2024 systematic review specifically evaluated robotic versus laparoscopic resections in difficult PS segments, demonstrating significantly lower blood loss, fewer transfusions, and shorter operative time in the robotic groups, without increases in morbidity or R1 rates.[20] A second meta-analysis, including more than 50,000 patients-one of the largest comparative assessments to date-confirmed that RLR significantly reduces conversions, overall morbidity, and major complications while improving R0 resection rates compared with LLR, especially in minor and parenchymal-sparing resections.[21] These data reinforce the biological plausibility of our findings: although PS segment resections remain anatomically demanding, the enhanced dexterity and visualization offered by robotics appear to counterbalance these challenges, resulting in perioperative outcomes comparable to AL segments.

One major finding of our study is a mismatch between intraoperative and postoperative outcomes: PS resections are more technically complicated but do not come with higher postoperative morbidity. Several likely factors account for this mismatch.

Robotic systems provide articulating wrists, stable three-dimensional optics, tremor filtration, and motion scaling features that facilitate delicate dissection in narrow spaces. Of particular relevance to PS segments are the challenging laparoscopic approaches due to the diaphragm, vena cava, and limited working angles. Better ergonomics and dexterity reduce unnecessary retraction, enable accurate bleeding point control, and ensure safe mobilization of liver segments in the right and superior locations. Several previous series have mentioned the fact that even though RLR increases the operative time when dealing with challenging segments, it coincides with decreased conversion rates and optimizes hemostatic precision.[1,4,6]

In our cohort, PS resections required the Pringle maneuver more frequently and for longer intervals. This is less likely to reflect a more dangerous operation than to demonstrate a greater use of strategic inflow occlusion during difficult transections. Data from robotic and laparoscopic series indicate that controlled, intermittent inflow occlusion reduces blood loss and enhances exposure without increasing postoperative liver dysfunction or complications.[1–3] Longer clamp times in PS cases likely result from proactive surgical planning rather than as a pure function of intraoperative difficulty.

Participating institutions represented high-volume hepatobiliary centers with established robotic programs. Several series have identified institutional experience and structured training as key determinants of reduced conversions and complications in minimally invasive liver surgery.[10] Some studies have stressed that proficiency in both laparoscopic and robotic liver resection accelerates the learning curve and expands the repertoire of cases manageable minimally invasively.[8–10] This concentration of expertise likely explains similar postoperative outcomes despite anatomical challenges.

Minor resections, especially anatomical segmentectomies and bisegmentectomies, prioritize functional liver parenchyma preservation. This is a particular advantage in cirrhotic or borderline functional patients. The robotic platform may facilitate anatomical resections in PS segments by guiding the precise dissection along intersegmental planes, minimizing collateral damage, and preserving inflow/outflow structures. This may explain why, even though PS resections required more operative effort, the postoperative complication rate did not increase.

There are several important implications of this study for clinical practice. Our findings support the conclusion that PS location alone should not preclude an RLR, provided surgeons have adequate experience and patients are appropriately selected. Historically, PS segments have been approached preferentially via open surgery due to technical constraints. Our data, in conjunction with recent European and global studies, suggest that robotics effectively shifts this paradigm. Patients undergoing PS resections should be informed that the operation may be longer and involve more frequent inflow occlusion, but that these factors do not translate into higher postoperative risk. This is an important distinction to ensure appropriate informed consent and expectation management. Given the longer operative time and use of refined dissection techniques, PS resections may require more operative resources. However, because postoperative recovery and hospital stay remain similar, the overall impact on healthcare resources may be modest, particularly considering the potential reduction in conversions and complications. These findings underscore the importance of structured robotic hepatobiliary training, including simulation, cadaveric labs, and mentored case progression, with particular attention to PS segments. Evidence suggests that hybrid training models—combining robotic and advanced laparoscopic experience—result in safer implementation and faster acquisition of skills.[22] Margin clearance was comparable between PS and AL resections across all analyses, and this is consistent with modern RLR oncologic series, which demonstrated robust R0 rates in robotic resections for both HCC and metastases.[8–10] This reinforces the role of robotic minor resections in oncologically demanding cases.

Emerging evidence also suggests that robotic technology may facilitate greater adherence to a parenchymal-sparing philosophy, which has become increasingly relevant in modern hepatobiliary surgery. Parenchymal-sparing liver resections have been associated with decreased postoperative liver dysfunction, improved regeneration, and preserved future liver remnant, particularly in cirrhotic or oncologically pretreated patients.[23–26] Several technical reports and narrative reviews suggest that the precision and stable magnified visualization of RLR enable surgeons to more closely follow anatomic planes in deep segments, thus tailoring the extent of resection to the lesion while minimizing unnecessary tissue loss.[27–29] In this context, the comparable postoperative outcomes in PS and AL resections within our cohort may partly be a reflection of the capability of the robotic platform to maintain high technical accuracy even in constrained operative fields.

Moreover, the consistency of our results across various matched cohorts stands in concert with large multicenter experiences demonstrating the reproducibility of the robotic approach across different practice settings. The international registry by Sijberden *et al*. of over 10,000 liver resections demonstrated that robotic procedures achieve superior "textbook outcomes" and reduced transfusion rates independent of case complexity and, therefore, strengthen the call for wider adoption of RLR, even for anatomically demanding locations.[6] As robotics continues to grow, structured training pathways-including simulation-based modules, dual-console mentoring, and standardized progression through successively more complex segments-can be expected to take on a particularly vital role in ensuring that such outcomes can safely be replicated outside high-volume centers.[21]

The strengths of this study include its large multicenter design, its exclusive focus on robotic minor resections, and its rigorous two-step propensity score matching strategy that took into account such relevant confounders as cirrhosis, number of lesions, anatomical resection, and gender. This allowed for a proper comparison of segmental location independent of baseline heterogeneity.

Limitations include the retrospective design, selection bias, and variability in technique among centers. In addition, the study focuses on short-term outcomes, and long-term oncologic follow-up was not available. Also in the literature, there is a lack of long-term oncologic data related to robotic resections of PS lesions. Although recent meta-analyses in hepatocellular carcinoma suggest that RLR may yield improved recurrence-free and overall survival as compared with open and laparoscopic approaches,[29] the available evidence is heterogeneous, with variable follow-up lengths and very limited stratification by segmental location. Comparable gaps persist for colorectal liver metastases and non-colorectal liver metastases, where robotic approaches have shown perioperative advantages but are at present supported by very limited survival data to enable one to establish equivalence or superiority.[30,31] Future prospective registries with long-term functional and oncological endpoints, such as the NONCOLMET Study,[32] will therefore be crucial to validate the sustainability of the short-term benefits we have recorded.

Cost-effectiveness analysis was not performed, although this remains a critical consideration as robotics spreads worldwide.

Finally, although this is the biggest PSM-focused robotic study published to date, further prospective or randomized evaluations would strengthen the evidence base.

Conclusion

In this multicenter European analysis, robotic minor liver resections in posterosuperior segments showed increased intraoperative complexity without significant differences in postoperative morbidity, mortality, or oncologic margins when compared with anterolateral resections. Such findings confirm that the robotic platform effectively overcomes the anatomical limitations of posterosuperior segments, ensuring safe and oncologically sound minimally invasive surgery if performed in experienced centers.

Future studies should focus on long-term oncologic outcomes, functional liver recovery, and cost-effectiveness to better define the overall value of robotic surgery in these challenging segments. Further work regarding standardized training pathways and emerging technologies, such as advanced imaging and augmented reality, might also enhance precision and broaden the safe adoption of robotic liver surgery in complex anatomical settings.

Author contributions

Conceptualization, S.C. and R.Me.; methodology, A.C. and G.C.; validation, F.D.B. and R.Me.; formal analysis, P.M. and A.B.; writing—original draft preparation, M.G.S. and R.Ma.; writing—review and editing, F.R. and T.P.; supervision, N.D.A. and P.P.; project administration, F.I. and A.L. All authors have read and agreed to the published version of the manuscript.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Institutional review board statement

This study did not require approval by the Ethics Committees because of its retrospective nature.

Data availability statement

The data presented in this study are available upon request from the corresponding author due to privacy reasons.

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Conflicts of interest

None declared.

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